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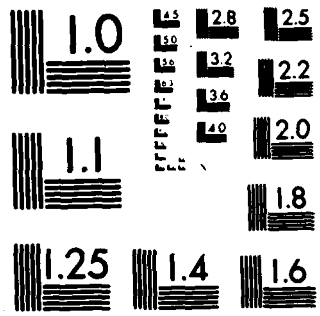

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CONTENTS

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UNIFIED THEORY OF THE POWER SPECTRUM OF LONG WAVELENGTH IONOSPHERIC ELECTRON DENSITY IRREGULARITIES

INTRODUCTION

The study of electron density irregularities and structures in the ionosphere has divided itself naturally into three regimes: the low, middle and high geomagnetic latitudes. These regimes have fundamentally different sources for the irregularities, associated with the degree of coupling to higher altitude magnetospheric phenomena. The coupling is related to the orientation of the geomagnetic fields as a function of magnetic latitude. At low latitudes, where the geomagnetic field tends to be horizontal, coupling to higher altitude magnetospheric disturbances is inhibited. At high latitudes the more vertical magnetic field promotes strong magnetospheric-ionospheric coupling. (For recent reviews of ionospheric structures and irregularities see Fejer and Kelley, 1980, Ossakow,1981, and Keskinen and Ossakow, 1983.) A fundamental quantity, which can be measured experimentally and computed theoretically, characterizing ionospheric structures and turbulence is the power spectrum of the density fluctuations. A theory which extends the Kolmogorov picture of fluid turbulence to unstable plasma systems [Sudan and Pfirsch,1982] has recently been applied to Type II electron density irregularities in the equatorial electrojet [Sudan 1983]. The concepts underlying this treatment are a development of previous studies [Kulsrud and Sudan, 1981; Sudan and Keskinen, 1977, 1979 Keskinen, 1981]. This theory [Sudan, 1983] predicts the absolute magnitude of the power spectrum as a function of wavelength in terms of a strength parameter $\nu_i \gamma_o / k_o^2 C_s^2 \equiv S$ which can also be interpreted as a Reynolds number that defines the level of the turbulence; ν_i is the ion-neutral collision frequency, C_s is the sound speed, $k_o = 2\pi/\lambda_o$, λ_o is the largest scale size involved in the turbulence and $\gamma_o(k_o)$ is the linear growth rate of the fluctuation whose wavelength is λ_o. The purpose of this letter is to show that this theory applies equally well and almost without significant modification to equatorial spread F, natural auroral electron density irregularities in the E and F regions, and artificial irregularities in barium clouds for wavelengths above the ion gyro-radius and below say ~ 10km. The predictions of this theory are in good agreement with the accumulated radar observations [Farley, 1979; Hanuise and Crochet, 1981a, 1981b] and the more recent rocket observations [Fejer and Kelley, 1980; Kelley, et. al., 1982; Prakash et. al., 1972 Keskinen et al., 1981; Singh and Szuszczewicz, 1983; Rodriguez and Szuszczewicz, 1983].

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THEORY

For low-frequency modes the ionospheric plasma in the E and F region can be modelled by two-fluid equations in which quasi-neutrality is assumed $n_e = n_i = n$, the pressure variations are taken to be isothermal, and the electron and ion inertia are both neglected. Because $8\pi n(T_e + T_i) << B_o^2$ where $\underset{\sim}{B}_o$ is the Earth's magnetic field, the perturbed magnetic fluctuations vanish and the electric field fluctuation are electrostatic $\underset{\sim}{E} = -\nabla\phi$ and we can write

$$\frac{\partial n}{\partial t} + \underset{\sim}{V}_d \cdot \nabla n + n\nabla \cdot \underset{\sim}{V} = -\nabla \cdot n\underset{\sim}{V} \quad (1)$$

$$-e(-\nabla\phi + \frac{1}{c}\underset{\sim}{V}_e \times \underline{B}) - \frac{T_e \nabla n}{n} - \nu_e m_e \underset{\sim}{V}_e = 0 \quad (2)$$

$$e(-\nabla\phi + \frac{1}{c}\underset{\sim}{V}_i \times \underline{B}) - \frac{T_i \nabla n}{n} + m_i g - \nu_i m_i \underset{\sim}{V}_i = 0 \quad (3)$$

$$\nabla \cdot \underset{\sim}{J} = e\nabla \cdot n(\underset{\sim}{V}_i - \underset{\sim}{V}_e) = 0 \quad (4)$$

In this set, the e and i subscripts refer to electrons and ions, respectively, $\nu_{i,e}$ is the charged particle neutral collision frequency, $\underline{g}$ is the acceleration due to gravity and the other symbols have and their conventional meaning. In the continuity equation (1) $\underset{\sim}{V}_d$ is the particle drift across the magnetic field. In the E-region where ions are unmagnetized, $\nu_i/\Omega_i \sim 10$, and electrons are magnetized, $\nu_e/\Omega_e \sim 3 \times 10^{-2}$; (Ω_i is the cyclotron frequency), the electrons drift at a velocity given by $\underline{V}_d = c\underset{\sim}{E}_o \times \underset{\sim}{B}_o/B_o^2$ where $\underline{E}_o$ is the ambient vertical static field. The ions are stationary and the electrons drift, $\underline{V}_d$ results in the electrojet current. In the F-region, on the other hand, $\nu_i/\Omega_i \sim 10^{-3}$, $\nu_e/\Omega_e \sim 10^{-4}$ i.e., both electrons and ions are magnetized and the ambient field $\underset{\sim}{E}_o$ causes the electrons and ions to drift at the same rate, so that no electric current is generated by $\underset{\sim}{E}_o$. However the much weaker gravitational field causes the ions to drift with respect to the electrons. Thus in the electron drift frame we set $\underset{\sim}{V}_d = (\frac{m_i c}{e})\, \underline{g} \times \underset{\sim}{B}_o/B_o^2$ the ion drift velocity and $\underset{\sim}{V} = \underset{\sim}{V}_i$ in Eq. (1).

Consider an electrostatic wave $\delta\phi = \tilde{\phi} \exp i(\underset{\sim}{k}\cdot\underset{\sim}{x} - \omega_k t)$ propagating in this medium such that $kL \gg$ where L is the scale length of the ambient electron density. Such a wave will be Landau damped by electrons free-streaming along $\underset{\sim}{B}_o$ unless $\omega > k_\parallel v_e$, $k_\parallel = (\underset{\sim}{k}\cdot\underset{\sim}{B}_o)/B_o$ and $v_e = (2T_e/m_e)^{1/2}$ is the electron thermal velocity. Now the low-frequency modes under discussion have $\mathrm{Re}\,\omega_k \approx \underset{\sim}{k}\cdot\underset{\sim}{V}_d \approx k_\perp V_d$. Thus

$$k_\parallel/k_\perp \approx V_d/v_e \approx \begin{cases} 10^{-3}, & \text{E region} \\ 10^{-6}, & \text{F region} \end{cases}$$

It is clear that these irregularities have an almost two-dimensional structure in both the E and F regions and we may consider the turbulent interactions between the different modes essentially as a two-dimensional system and isotropic in the plane perpendicular to $\underset{\sim}{B}_o$.

At the equator the magnetic field has no dip and the ambient electron density gradient ∇n_o, $\underset{\sim}{B}_o$ and the mean electrojet drift $\underset{\sim}{V}_d$ are orthogonal to each other. This special geometry has been utilized in the study of electrojet driven irregularities. However in the auroral regions, while $\underset{\sim}{V}_d$ and $\underset{\sim}{B}_o$ are orthogonal, ∇n_o and $\underset{\sim}{B}_o$ are not because of the large dip of the earth's magnetic field. In this situation because the modes of interest still have $k_\parallel \ll k_\perp$, the component of the density gradient along the magnetic field $\underset{\sim}{B}_o\cdot\nabla n_o/B_o$, plays no role in the dynamical evolution of these modes so long as $(\underset{\sim}{k}\cdot\underset{\sim}{B}_o)(\underset{\sim}{B}_o\cdot\nabla n_o/n_o B_o^2) \gg 1$ (we do not consider $\underset{\sim}{j}\cdot\underset{\sim}{B} \neq 0$ driven modes here). The auroral case is equivalent to the equatorial situation if ∇n_o is replaced by $\nabla_\perp n_o$ which is the component of the gradient perpendicular to $\underset{\sim}{B}_o$. Thus the analysis for the equatorial E and F regions could be extrapolated to any latitude provided the appropriate density gradient is taken into consideration.

In the set (1) - (4) the principal nonlinear interaction takes place through the term $\nabla\cdot n\underset{\sim}{V}$ in Eq. (1). Denoting

$$\phi_{\underset{\sim}{k},\omega} = \int\frac{dt}{2\pi}\int\frac{d^2x}{(2\pi)^2}\,\phi(\underset{\sim}{x},t)\exp i(\omega t - \underset{\sim}{k}\cdot\underset{\sim}{x})$$

$$n_{\underset{\sim}{k},\omega} = \int\frac{dt}{2\pi}\int\frac{d^2x}{(2\pi)^2}\,n(\underset{\sim}{x},t)\exp i(\omega t - \underset{\sim}{k}\cdot\underset{\sim}{x})$$

it can be shown that this system of equations can be written in the form

$$(\omega - \omega_{\underset{\sim}{k}})\, n_{\underset{\sim}{k},\omega} = \int d\omega' d^3k'\, V_{\underset{\sim}{k},\underset{\sim}{k}',\underset{\sim}{k}''}\, n_{\underset{\sim}{k}',\omega'}\, n_{\underset{\sim}{k}'',\omega''} \tag{5}$$

with $\underset{\sim}{k}'' = \underset{\sim}{k} - \underset{\sim}{k}'$ and $\omega'' = \omega - \omega'$. In the equatorial E-region we have shown previously [Sudan and Keskinen, 1977; Sudan, 1983] that the Hall current driven $\underline{E} \times \underline{B}$ instability has frequency and growth rate

that

$$\mathrm{Re}\,\omega_{\underset{\sim}{k}} = \underset{\sim}{k}\cdot\underset{\sim}{V}_d/(1 + \psi) \tag{6a}$$

$$\mathrm{Im}\,\omega_{\underset{\sim}{k}} \equiv \gamma_{\underset{\sim}{k}} = \frac{\psi}{1 + \psi}\left\{\frac{(\Omega_e(\underset{\sim}{k}\cdot\underset{\sim}{V}_d)^2}{\nu_e(1 + \psi)kV_d}\,\frac{1}{n_o}\,\frac{dn_o}{dz} - \frac{k^2 C_s^2}{\nu_i}\right\} \tag{6b}$$

and

$$V_{\underset{\sim}{k},\,\underset{\sim}{k}',\,\underset{\sim}{k}''} = \frac{\beta(\underset{\sim}{k}'\cdot\underset{\sim}{V}_d)}{n_o}\,\frac{\underset{\sim}{k}'\cdot\hat{z}}{k'^2} \times \underset{\sim}{k}'' \tag{6c}$$

$$\beta = (\nu_i/\Omega_i)(1 + \psi)^{-1}$$

$$\psi = \nu_e\nu_i/\Omega_e\Omega_i$$

To extend these results to the E-region at arbitrary latitude one need only replace $\partial n_o/\partial z$ with $\nabla_\perp n_o$. The nonlinear terms remain unchanged.

The Rayleigh-Taylor and $\underset{\sim}{E} \times \underset{\sim}{B}$ gradient drift instabilities have been invoked to explain low and high latitude F-region density irregularities, respectively (see recent reviews of Ossakow, 1981 for the low latitude ionosphere and Keskinen and Ossakow, 1983 for the high latitude case). We now show that the structure of eq. (5) is unchanged for Rayleigh-Taylor and $\underset{\sim}{E} \times \underset{\sim}{B}$ gradient drift modes. In the drift frame of the electrons the ion drift is given by [x,y,z are the vertical east/west, and north/south coordinates; $\underset{\sim}{B}_o = B_o\hat{\underset{\sim}{z}}$ at the magnetic equator]

$$\underset{\sim}{V}_d \equiv \underset{\sim}{V}_{io} = \begin{cases} \underline{g} \times \hat{\underline{z}}/\Omega_i & \text{low latitude} \\ (\nu_i/\Omega_i)(c\underset{\sim}{E}_o/B_o) & \text{high latitude} \end{cases} \tag{7}$$

and for low latitudes the perturbed electron and ion drifts are

$$\delta V_e = -\frac{c}{B_o}(\nabla\delta\phi \times \hat{z}) + 0\left(\frac{\nu_{ei}}{\Omega_e}\right) \tag{8}$$

$$\delta V_i = -\frac{c}{B_o}(\nabla\delta\phi \times \hat{z}) - \frac{\nu_i}{\Omega_i}\frac{c}{B_o}\nabla\delta\phi \tag{9}$$

Note that $\nu_e/\Omega_e \ll \nu_i/\Omega_i$ in F-region. From (4), (8) and (9) $\delta\phi$ and δn are related by

$$\delta\phi = -i\frac{\Omega_i}{\nu_i}\frac{B_o}{c}\frac{k\cdot V_{io}}{k^2}\frac{\delta n}{n_o} \tag{10}$$

to linear order in δn . Furthermore from (9) and (3)

$$\nabla\cdot\delta V_i = -\frac{\nu_i^2}{\Omega_i^2}(m_i\nu_i)^{-1}\nabla\cdot\left(e\nabla\delta\phi + T_i\frac{\nabla\delta n}{n_o}\right), \tag{11}$$

and (9) (10) and (11) when substituted into (1) yield (5) with

$$\mathrm{Re}\,\omega_k = k\cdot V_{io} \tag{12a}$$

$$\mathrm{Im}\,\omega_k = \frac{\Omega_i}{\nu_i}\frac{(k \times \hat{z}\cdot\nabla_\perp n_o)}{n_o}\frac{k\cdot V_{io}}{k^2} - \frac{\nu_i}{\Omega_i^2}k^2C_s^2 \tag{12b}$$

$$V_{k,\,k',\,k''} = \frac{\Omega_i}{\nu_i}\frac{k'\cdot V_{io}}{n_o}\frac{k'\cdot\hat{z} \times k''}{k'^2} \tag{12c}$$

Note that the expressions for the nonlinear matrix element $V_{k,k',k''}$ of (6c) and (12c) are identical in structure. Similar relations can be obtained for the high laltitude case.Thus the nature of the nonlinear interaction of the Rayleigh-Taylor and $\underline{E} \times \underline{B}$ modes in the equatorial and high latitude F-region is identical to the $\underline{E} \times \underline{B}$ instabilities of the E-region.

Equation (5) defines the interaction of modes k, k', k'' . If $\mathrm{Re}\,\omega_k$ is non-dispersive i.e. $\partial\omega_k/\partial k$ is independent of k , all possible k' and k'' will interact with k provided only that they satisfy the triangular equality $k'' = k - k'$. If ω_k is dispersive than only those modes which also simultaneously satisfy $\omega_{k''} = \omega_k - \omega_{k'}$ contribute to the interaction.
Depending upon the shape of $\omega(k)$ this reduces the number of interacting modes from a continuous to a small discrete set. The physical repercussion of this

difference in the number of interacting modes is to cause a strong interaction in the non-dispersive case which results in the nonlinear self-damping $\Gamma_{\underset{\sim}{k}}$ of the mode [Kadomtsev, 1963; Kraichnan, 1959]. This self-damping may also be interpreted as a spread $|\Delta\omega_{\underset{\sim}{k}}| = \Gamma_{\underset{\sim}{k}}$ in the eigenfrequency $\omega_{\underset{\sim}{k}}$. For the dispersive case the interaction is weak and the linear eigenfrequencies $\omega_{\underset{\sim}{k}}$ are retained even in the nonlinear development (so called weak-turbulence, see Sagdeev and Galeev, 1969). For the non-dispersive modes under consideration here the turbulence is considered "strong".

Because we are dealing with fully developed turbulence, fluctuations with all possible wavelengths in a certain range are present. Define the power spectrum $I_{\underset{\sim}{k},\omega} = \langle|n_{\underset{\sim}{k},\omega}|^2/n_o^2\rangle$ where $\langle\ \rangle$ denote an ensemble average. Also $I_{\underset{\sim}{k}} = \int d\omega\, I_{\underset{\sim}{k},\omega}$ and the energy in the fluctuations $U_{\underset{\sim}{k}} \equiv \mu I_{\underset{\sim}{k}}$ where μ is a constant. The total energy density

$$U(\underset{\sim}{x}) = \mu\int d^2k\ I_{\underset{\sim}{k}}$$

$$= 2\pi\mu\int_0^\infty d(\ln k)\ k^2 I_k \quad \text{for isotropic power spectrum}$$

Thus $\varepsilon(k) = k^2 I_k$ is the energy in the logarithmic interval $d(\ln k) = dk/k$. An estimate for the self-damping Γ_k from a dimensional analysis of (5) proceeds as follows. Assuming that the interaction is dominated by modes with $k \sim k' \sim k''$,

$$\Gamma_k = |\Delta\omega_k| = |\omega - \omega_k| \sim V_{k,\,k',k''}|n_k|k\Delta k \simeq \beta k V_d(k I_k^{1/2}) \tag{13}$$

where we have employed (6c) set $\Delta k \sim k$ and $\langle|n_k|^2/n_o^2\rangle \sim k I_k^{1/2}$. Furthermore from (2) and (4) we find in the linear approximation that

$$\underset{\sim}{v}_{\underset{\sim}{k}} = \beta(\underset{\sim}{k}\cdot\underset{\sim}{V}_d)\,\frac{\underset{\sim}{k}\times\hat{z}}{k^2}\,\frac{n_k}{n_o} \tag{14}$$

so that

$$\Gamma_k \equiv \Delta\omega_{\underset{\sim}{k}} \approx k^3\ V_k \approx k\Delta V \sim \frac{2\pi\Delta V}{\lambda} \sim \tau_k^{-1} \tag{15}$$

where ΔV is the velocity of an eddy of scale size λ . The self-damping is therefore related to the inverse of the "eddy-turnover" time τ_k .

Kolmogorov's theory of fluid turbulence states that the fluid energy contained in the interval Δk is transferred into the interval $2\Delta k$ in an eddy turnover time τ_k. This is to say that $(d/d\ln k)\varepsilon_k\tau_k$ is conserved in the inertial regime. In plasma turbulence however the energy may be augmented or diminished by the linear growth or damping of the waves. Thus we have [Kulsrud and Sudan, 1982; Sudan and Pfirsch, 1982]

$$\frac{d}{d\ln k}(k^2 I_k \Gamma_k) = \gamma_k k^2 I_k \tag{16}$$

where γ_k is the linear growth/damping rate. Substituting for Γ_k from (13) we obtain a first order equation which is easily solved. Now $\gamma_k = \gamma_o k^2 G$ is valid for both E and F regions with appropriate choice of γ_o and G [See (6b) and(2b)]. Define a strength parameter $S=\gamma_o/k_o^2 G$ where k_o is the longest wavelength in the system. The solution of (5) for $I_{k_o} = 0$ is then given by

$$I(x) = x^{-8/3}\left[1-x^{-2/3} - \frac{1}{2S}(x^{4/3} - 1)\right]^2 \tag{17}$$

and

$$I(x) = \beta^2 k_o^2 (k_o V_d/\gamma_o)^2 I(k)$$

where $x = k/k_o$. Thus the spectrum of (17) originally established for the equatorial E-region [Sudan, 1983] should be universally valid for the E and F regions at all latitudes for almost two-dimensional modes governed by the set of Equations (1) to (4). Notice that the difference in the nature of instabilities does not reveal itself in the spectrum because the nonlinear term $\nabla\cdot n\bar{V}$ which established the interaction between the modes is the same. For $x > S^{1/2}$ the modes are linearly damped but the spectrum will extend to $x \sim S^{3/4}$ before it vanishes. Then the range of damped modes excited by energy transfer from unstable modes is given by $\Delta x \simeq S^{1/4} - S^{1/2}$.

DISCUSSION

For parameters typical of the equatorial and high latitude E and F regions $S_o > 10^4 - 10^6$ and $\lambda = 2\pi/k_o$ may range from 1-10 km. In the inertial range therefore $I(k) \propto k^{-8/3}$. This power law dependence and associated spectral index is consistent with previous theoretical and experimental studies. Fig. 1 shows a sample power spectrum of the density fluctuations resulting from the numerically obtained evolution of the Rayleigh-Taylor

instability in the equatorial F-region ionosphere [Keskinen et al., 1981]. Good agreement is seen between the theoretical prescription for the power spectrum, eq. (17), and the numerical results. Similar power laws and spectral indices are also observed in theoretical and numerical studies of the E x B in the auroral ionosphere [Keskinen and Ossakow, 1982, 1983] and in plasma (barium) clouds [Keskinen et al]., 1980]. In addition, the theoretically derived power spectrum, eq. (17), is consistent with rocket observations of intermediate scale size density fluctuations in equatorial spread F [Keskinen et al, 1981, Szuszczewicz et al., 1980; Kelley et al., 1982; Kelley et al., 1982]. Fig. 2 shows a sample experimentally obtained power spectrum taken from Keskinen et al. [1981]. Similar power laws are also observed with satellite measurements in the high latitude F region ionosphere [E. Szuszczewicz, private communication].

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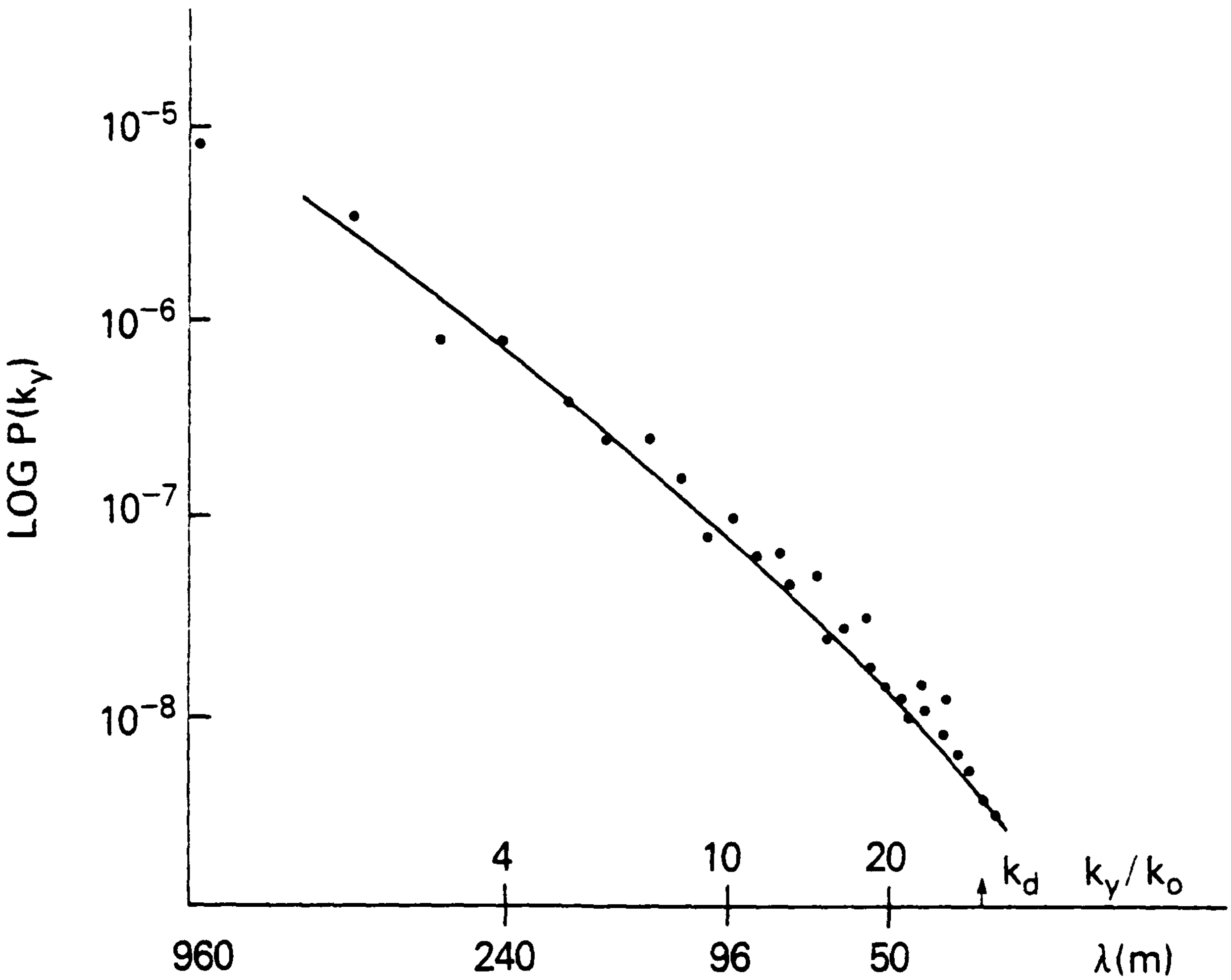

Fig. 1 Numerically obtained vertical wave number spectra [Keskinen et al, 1981] of Rayleigh-Taylor instability. The symbol $k_o = 2\pi/960$m and the cutoff valve $k_d = 30$. The continuous line is obtained from eq. (17).

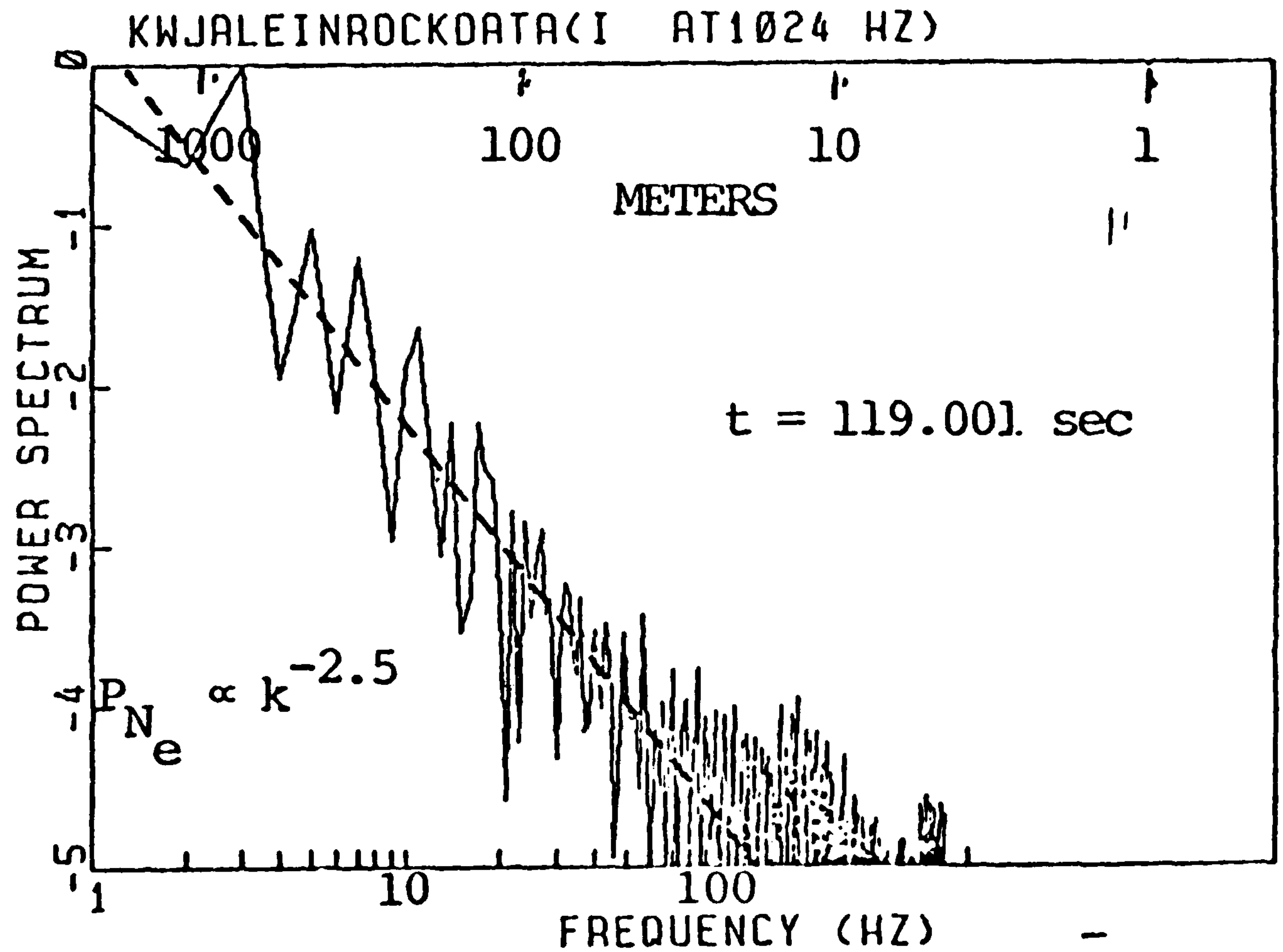

Fig. 2 Experimentally obtained power spectra of density fluctuations [Keskinen et al., 1981] in equatorial spread F ionosphere. Power spectra are plotted in dimensionless units. Straight lines are drawn with indicated slope.

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